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National Ignition Facility Target Diagnostic waveform digitization

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1. Mission Statement

The purpose of this document is to assess various technologies in *electrical waveform digitization* for applications at the National Ignition Facility (NIF), more specifically, the Target Diagnostic (TD) department. The findings and recommendations in this memo are meant to inform decisions for future diagnostic implementations and to guide plans for upgrades to existing systems that, due to age or inherent deficiencies, require renewal.

2. Executive Summary

We assess various technologies in electrical waveform digitization to inform decisions for future target diagnostics and upgrades on the NIF. We perform a qualitative technology assessment based on gathered information and established guidelines in benefit, cost, and risk.

The technologies under assessment include ADC, CRT, and switching capacitor digitizers. CRT digitizers are very expensive, have long lead times, and have relatively poor performance characteristics. They are a dying technology. There is only one manufacture of commercially available switched capacitor digitizers, which employs immense channel density, 12-bit resolutions, and sample rates up to 5 GS/s. They provide a very significant cost savings with a bandwidth limited to 500 Mhz. These are an under developed technology with an uncertain future.

The technology of ADCs has many competitors in the marketplace, driving lower costs, continuous innovation, and assuring long-term support. They have high performance characteristics in accuracy, stability, linearity, Mean-Time-Between-Failures (MTBF), and jitter. NIF has a legacy of four-channel, 8-bit digitizers that are large and expensive.

The vast majority of new diagnostics and upgrades are likely to benefit most from compact ADC technology and their higher, 10+ bit resolution offerings. There are sub-Ghz sample rate units with significant cost but most NIF diagnostics may benefit in the 1-2 Ghz bandwidth digitizers employing 10 and 12 bit resolutions.

3. Program Overview

Here we explain the high-level program purpose, the program description, and the diagnostic system description that is pertinent to the digitizer technology assessment performed in Section 4.

3.1. The National Ignition Facility

The NIF is the world's largest and most energetic laser facility ever constructed. It was built for the main purposes of nuclear weapons research, fusion energy research, and basic science. It contains 192 laser beams that focus on a fusion fuel target about the size of a pencil eraser, with the intent to compress, heat, and create a self-sustaining fusion reaction that burns all of the fuel. To perform this mission, the NIF needs to understand and predict the behavior of the target and laser throughout the shot process, which requires diagnostics.

3.2. NIF Target Diagnostics

Target diagnostics on the NIF are responsible for measuring all relevant parameters of an experimental laser shot-on-target. These parameters include neutrons, x-rays, gamma rays, laser light, shock waves, and others. Relevant parameters are defined by the experimental scientists and the experiment. TD employs a large scale complex multidisciplinary suite of diagnostic systems which are organized by engineering architectures.

3.3. Scope Based Diagnostic Systems (SBDS)

SBDS on the NIF are many and varying, employing a wide range of methods for measurements of neutrons, x-rays, gammas, and other experimental quantities of interest. However, they all share a common architecture in the method for data transmission and recording, enabled by the fact that eventually the physics measurement is transduced into a transient *time-varying voltage signal*. High level physics requirements are established for each system and these flow down into engineering requirements, of which some are relevant to the voltage signal to be measured and the recoding system performing the measurement. Ignoring outliers, listed here are the most relevant ranges of specifications of concern to this assessment.

- Analog bandwidth = 0.5-6 Ghz
- Sample rate = 2-5 GS/s
- Minimum expected input voltage = 10-100 mV
- Maximum expected input voltage = 5-20 V
- Maximum unexpected input voltage = 100-1500 V

- Total signal resolution = 40-80 db (6.4-13 ENOB[1])
- Transmission line impedance = 50 ohm

Also of concern is the lifetime cost to operate, which depends on upfront costs, planned maintenance, end-of-life replacement, etc. Calibration requirements and unplanned maintenance contribute not only to increased costs, but also to diagnostic down times and potential for loss of shot data, which is difficult to fully quantify.

4. Technology Risks Summary and Readiness Assessment

4.1. Strategic Process

We performed a qualitative technology assessment based on gathered information and established guidelines. The process for this assessment focused first on the definition of the mission statement as outlined in Section 1. Next, we sought to understand the description and goals of the overall project and the end users of the proposed technology, as shown in Section 3. Here we defined a subset of performance and cost metrics for use in assessing the technologies. Risk is also considered as it relates to technology maturity and the number of source manufacturers.

Next, information gathering was performed with a focus on known digitizer manufacturers and the technologies they currently offer. Most of the information was retrieved via the Web using equipment specification and data sheets, wiki pages, and new articles. Additionally, direct correspondence with manufacturers via email and phone conversations was done to clear up ambiguities. The assessment then follows.

4.2. Assessed Technologies

CRT digitizers employ a hybrid scan-conversion principle that first projects the signal onto a CRT screen. It then records a digital photograph of the slow decay phosphor by use of a CMOS camera and stores it in video memory. Image processing and defect correction is employed to reduce the digital image to an x-y trace representation of the original signal that is then saved and available for download via network connection.

The *switched capacitor digitizer* continuously samples the analog input signals into a circular memory buffer, an array of capacitor cells. Record lengths are limited by the size of the array, and bandwidths are limited by the array size and cell time constants. When triggered, all the analog memory buffers are frozen, thus allowing a slower ADC digitization process to occur.

[1] Effective number of bits (ENOB) is a measure of the dynamic performance of an ADC and its associated circuitry. The number of bits used to represent the analog value specifies the resolution of an ADC; however, all real ADC circuits introduce noise and distortion. In practice ENOB is typically 1-1.5 bits lower than stated resolution, but may better or much worse.

The direct conversion *Analog-to-Digital Converter* (ADC) is a well-established technology for use in transient electric signal recording. Here a continuously varying analog signal is transformed into discrete levels, a quantized digital signal and then stored in memory. Typically, time-interleaved ADCs are employed at our frequencies of interest.

The digitizer technologies of interest in this assessment have a number of common elements. First, they all employ an analog front-end and thus an analog bandwidth; at a minimum, the incoming signal must first pass through a connector and a transmission line. All of these technologies accept autonomous computer control and communication and will output recorded data and status information.

4.2.1. CRT Digitizer Assessment

There is only one current manufacture of CRT digitizers, Greenfield Technology, a French company. These units are very expensive, at roughly $70k per channel, and have long lead times when purchasing. CRT technology has fully matured; however, its performance characteristics as a scientific recording device have been surpassed in almost all areas by solid state devices. Note also that Greenfield is building these using an old stock of vacuum tubes, for which there is no current manufacturer.

Since they are based on a high voltage bias vacuum tube technology, they have short life cycles of approximately 2000 hours. They have relatively large nonlinearities that are corrected through calibration; however, they have proven relatively unstable over long periods of time, requiring expensive recalibration and priceless loss of data in some cases. Short MTBFs require a skilled technician staff and spare parts on hand for repair and often the repairs require expensive servicing at the manufacturer in France!

There are two areas where this technology should be considered. One is for applications that expect to produce very high un-attenuated voltage inputs before or after the desired data signal of interest. These scopes record signals in the range of 0.01 to 5 volts, but can withstand up to 2kV without damage or recovery time issues. However, one should consider how other technologies could be employed to obtain the same function. The second area to consider is the narrow requirement of a signal channel resolution of 10 bits at bandwidths 5-7 Ghz.

4.2.2. Switched Capacitor Assessment

There is only one manufacture of commercially available switched capacitor digitizers, CAEN Electronic Instrumentation, an Italy based company. CAEN offers a couple models that excel in resolution at 12-bit and a high sample rate up to 5 GS/s. These models are available at about $700 per channel, which is a very significant cost savings. There is a trade-off in bandwidth, which is limited to 500 Mhz. Slightly better performance can be achieved with ADC based digitizers, but at a very large cost.

These units can be purchased with up to 32 channels on a single VME card, an immense channel density by any standard. Of note is that these units, like the CRTs, have only a single non-varying sensitivity range, which should not be of too much concern given our move towards front-end remote attenuators. There is no information on max input voltage however, and this needs to be investigated.

In the early 90’s a DAC of this kind was lauded as the “world’s fastest digitizer,” but there has been little commercial interest in them, impeding development. The early units were difficult to calibrate, unstable, and nonlinear, and it is unclear how well CAEN has been able to solve these issues. The spec sheets provide only the very basic of information, and inquiries for a performance report have been unsuccessful. Due to the potential cost savings, we should consider extensive testing.

4.2.3. ADC Digitizer Assessment

Data conversion in general has a long history going back to the 1700s, and to the 1800s when restricting interest to electrical data. The solid-state technology of the 50’s and 60’s increased the usefulness of ADCs; however, their slow speed limited their value in high-energy physics research, our application. It wasn’t until the 1980’s that ADC digitizers garnered widespread use in this area, and they have been advancing steadily ever since. ADC’s are relatively cheap compared to the technology they replaced, photographing of Rossi oscilloscope traces.

The technology of ADCs has significant advantages and there are many competitors in the marketplace, which is sure to keep costs reasonably low. Given the large market for these devices, this feeds continuous innovation and assures long-term support for calibration, maintenance, and end of life replacements. Note however, that some manufactures update their models frequently, meaning exact drop-in replacements will not be available long term and higher costs result. The combination of maturity and continuous innovation of the technology has led to high performance in accuracy, stability, linearity, MTBF, and jitter.

In the area of ADC digitizer technology, there are two sub-regions to consider. NIF has a legacy connection to the Tektronix DPO platform, a four-channel, 8-bit digitizer, with bandwidths 1-6+ Ghz, utilizing a full user console interface. These units are rather large, taking 8U of rack space and have a significant thermal footprint, thus requiring extensive cooling. Agilent, LeCroy and Rohde & Schwarz are other manufacturers producing similar performing units, all at a cost of between $10k and $20k per channel.

The other ADC platform of interest is that of the compact digitizer comprising either the 1U standalone unit or the digitizer card using standards of PCI, compact PCI, VME, and a half dozen others. Since they do not employ the user interface, they have about as small a footprint as can be reasonably attained and a much-reduced need for cooling. These units are available in moderately high bandwidth ranges from 1 to 6 Ghz, but at the higher bandwidths, they are unlikely to outperform the existing Tektronix units currently installed. Additionally, the 8-bit units do not provide a significant cost savings.

Where we have the greatest potential to benefit from the compact digitizer ACD technology is in their higher, 10+ resolution offerings. Increased resolution reduces channel count needs and there are a number of manufactures producing 10, 12, 14, and 16 bit digitizers. The trade-off to higher resolution is lower bandwidth, and this is the key metric to gauge against requirements. A study of the field shows that digitizers of the highest resolutions are specified with sub-Ghz sample rates but show a significant cost savings (1/2).

The sweet spot for most NIF diagnostics is in the 1-3 Ghz bandwidth digitizers employing 10-12 bit resolutions. The combination of moderately high bandwidth and resolution is relatively new and is still developing. To date, the manufactures of Acqiris (recently purchased by Agilent) and Greenfield Technology have the only models that meet these high standards, however competing manufactures are likely to catch up, thus reducing relativity high costs.

5. Conclusion

In this document we have assessed three technologies in the application of electrical waveform digitization. We conclude that all three may have some use at the NIF and should be considered for applications where their unique attributes are needed. That being said, the vast majority of new diagnostics and upgrades are likely to benefit most from compact ADCs currently marketed by GreenField Technologies (models GFT6012 and GFT6022) and Acqiris (models U5303A and U1065A). These models provide bandwidths in the range of 1-3 Ghz, resolutions of 10-12 bits, sample rates of 2-10 GS/s, and are well suited to 80% of the diagnostic systems currently employed at the NIF.

6. References

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